Proposal to the National Science Foundation

CMS Construction Project

Draft of August 30, 1996

Project Summary

In this proposal, a request is made on behalf of the eight NSF supported university groups who are members of the Compact Muon Solenoid (CMS) collaboration and who have the exciting opportunity to contribute to the construction of the CMS detector at the CERN Large Hadron Collider (LHC). These groups now need the funding support to profit from this opportunity. CMS will undertake an experimental investigation of the interactions of protons on protons at a center of mass energy of 14 TeV. In order to explore the TeV mass scale, the LHC is designed to operate at very high luminosity ($\geq 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$); this produces a challenging experimental environment. The physics program includes studying electroweak symmetry breaking and the origin of mass, investigating the properties of the t-quark, searching for new heavy gauge bosons, probing quark and lepton substructure, looking for supersymmetry and generally seeking any new phenomena beyond the Standard Model. The LHC project was approved by CERN Council on December 15, 1994 for construction at CERN in the LEP tunnel. CMS was approved on January 31, 1996. Without doubt, the LHC will be the major instrument for high energy research beyond the Standard Model in the first quarter of the next century. It is surely important for US groups to take part in this exciting research enterprise. Each of the eight NSF groups has important and well-defined responsibilities within the CMS collaboration based on their expertise and previous work. After a brief description of the CMS experiment and the role of these groups, the NSF portion of the CMS construction project funding request is presented.

Contents

1 Introduction

1.1 Physics Motivation

Our current understanding of the basic building blocks of matter and their interactions is encapsulated in the theoretical framework of the Standard Model. The Standard Model has provided a remarkably good description of both electroweak data from LEP and SLC experiments, and hadronic data from CDF and DØ at the Tevatron. However, there are crucial limitations to the Standard Model that make it important to investigate physics at the TeV scale. A few examples, some of which will certainly take us beyond the Standard Model, are:

- Within the mathematical structure of the Standard Model, the required gauge symmetry realized in its simplest way implies that all particles are massless. The cleanest mathematically consistent way of introducing mass in the Standard Model requires the Higgs mechanism. While no Higgs particle has been detected to date, masses below ~60 GeV have been excluded by experiment; current theoretical understanding eliminates a Higgs particle with mass above ~1 TeV. It is surely important to investigate the mass region between these two limits.

- Even though the t-quark has now been observed in both CDF and DØ, little is known experimentally about its properties. The fact that the t-quark is so much more massive than the other quarks makes it exceptional among the fermions.

- It is conceivable that new forces may manifest themselves at LHC energies in the form of massive bosons similar to Z^0 and $W^{\pm}$. Heavy charged bosons can be found by seeking events with high-p_t. isolated leptons and large missing E_t.

- Another intriguing possibility is that quarks consist of other particles bound by some new force. This would cause the scattering of quarks at high transverse energy to differ from the QCD predictions. An indication of such quark compositeness would be an excess of hadronic jet events at high transverse energy. Evidence for lepton substructure would be a deviation from the expected Drell-Yan contribution to the lepton pair spectrum.

- The unification of different forces, or the realization that two apparently distinct forces were different aspects of one basic interaction has been of enormous importance in the history of physics. Following the unification of electricity and magnetism into electromagnetism, and its subsequent unification with the weak interactions (the Standard Model), great hope has been held out for a further unification with the strong interactions. For this to be possible at some high energy scale (~10^{15} GeV) there is evidence from the observed running of the coupling constants with energy, that new physics should materialize at an energy of around 1 TeV.

- The most profound unification that one might hope for in particle physics would show the fermionic particles of matter and the bosonic mediators of the fundamental interactions as different aspects of the same underlying structure. Such a unification is provided by supersymmetry, which predicts a new particle for every one we have observed so far, as well as several others required for consistency. None of the predicted particles have been observed so far, but for the theory to be relevant to electroweak symmetry breaking, they must appear at or below the TeV mass scale.

The *only* presently approved accelerator capable of investigating all such phenomena is the LHC, which will be built in the LEP tunnel at CERN. In order to enable studies of rare phenomena at the TeV scale, the LHC is a 14 TeV proton-proton collider designed to operate at a luminosity up to $2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. It is clear that the most significant questions in our current understanding of elementary-particle physics will be addressed at the LHC accelerator. It is also clear that if the US is to maintain its leading position in science, then US participation in the LHC program is absolutely essential. In no other way can this country continue to participate in frontier research and technology and train future scientists in this important field.

Two general-purpose detectors to investigate these and other phenomena have been approved for the LHC accelerator. These are the CMS (Compact Muon Solenoid) and ATLAS (A Toroidal LHC ApparatuS) detectors.

1.2 Overview of CMS

The CMS detector is designed to function at the highest luminosities available at the LHC. The detector has a high-field (4T) superconducting solenoid with a compact muon spectrometer outside and hadronic and electromagnetic calorimeters (HCAL and ECAL) inside. At the core of the detector system is the central tracker consisting of pixel detectors, silicon microstrip devices and gas microstrip chambers. In order to detect new physics signatures efficiently, identification of muons, electrons and photons has been emphasized. CMS is described extensively, including R&D and construction details, in the CMS Technical Proposal [3]. The CMS collaboration consists of some 1500 members from 140 institutions in 30 countries. The US component of CMS comprises more than 20% of the total. The CMS collaboration has assigned leadership responsibility to US groups for the HCAL and forward muon (EMU) systems, as well as associated aspects of the Trigger and Data Acquisition system and the Luminosity Monitor. In addition, US groups have been assigned important and well-defined responsibilities in the ECAL, Tracking and Computing/Software systems.

1.3 US Participation in CMS

A US team has been formed and has joined the CMS collaboration. This team consists of some 320 physicists and engineers from 38 US institutions (34 universities and 4 national laboratories). Of these groups, 32 have DOE base program support and 8 have NSF base program support. The US part of the CMS experiment was described in the September 8, 1995, Letter of Intent [1]. In that document, the project was discussed in some detail and an attempt was made to identify the amount of financial support requested from both DOE and NSF. It also contains the coherent sum of the entire US CMS project while underlining the

NSF and DOE group activities. Governance aspects of US CMS are covered in the US CMS Project Management Plan [2]. In separate proposals last year, the DOE groups and the NSF groups sought monies in support of the FY96 R&D phase. With this proposal we seek NSF support for the CMS project costs including support for the FY97-FY99 R&D program. We discuss the CMS subsystems that involve the serious and well-defined responsibilities of the NSF groups and underline the context of these responsibilities. Finally we include the funding profile taking us through FY05 that has been presented to US CMS by the NSF.

The current total base-budget of these eight NSF groups is approximately $2.5M *per annum* and covers a wide range of research activities involving experiments at CERN, DESY and Fermilab. Eventually all of these experiments will come to an end and these groups' research plus associated base funding will be devoted primarily to CMS. Even so, funding for CMS specific R&D (see accompanying proposal) and funding for CMS construction must be additional to the existing base. It is therefore our intention that this current proposal will be incorporated into an NSF Major Research Equipment (MRE) proposal to cover CMS R&D and construction costs.

1.4 NSF-Supported Group Involvement in CMS

In the following table we show the US CMS institutes with specific responsibilities in the individual subsystems: Endcap Muon (EMU), Hadron Calorimeter (HCAL), Trigger/DAQ, Electromagnetic Calorimeter (ECAL), Tracking and Computing/Software. The NSF groups are at the following universities:

The University of California, Los Angeles (P. Schlein (PI), S. Erhan, and J. Zweizig); The University of California, San Diego (H. Paar (PI), G. Masek and M. Sivertz); The University of Illinois, Chicago (M. Adams (PI), M. Chung and J. Solomon); The Johns Hopkins University (C-Y. Chien (PI), B. Barnett, D. Gerdes, A. Gougas, G. Hu and A. Pevsner); The University of Nebraska, Lincoln (G. Snow (PI), S. Atkins, W. Campbell, D. Claes, M. Hu and C. Lundstedt); Northeastern University (S. Reucroft (PI), G. Alverson, H. Fenker, P. Hanlet, J. Moromisato, Y. Musienko, T. Paul, D. Ruuska, J. Swain, L. Taylor, E. von Goeler, D. Wood and T. Yasuda); University of Notre Dame (R. Ruchti (PI), B. Baumbaugh, J. Bishop, N. Biswas, J. Warchol and M. Wayne); Virginia Polytechnic Institute and State University (L. Mo (PI), K. Blankenship, B. Lu and T. A. Nunamaker).

NSF Groups	Muon	HCAL	Lumi	Trigger/DAQ	ECAL	Track	Computing
UCLA			✔	✔			
UC San Diego				✔			
U. of Illinois, Chicago		✔					
Johns Hopkins						✔	✔
Nebraska			✔				
Northeastern	✔			✔	✔		✔
Notre Dame		✔					
Virginia Tech		✔					

DOE Groups	Muon	HCAL	Lumi	Trigger/DAQ	ECAL	Track	Computing
Alabama	✔						
Boston		✔					
Brookhaven					✔		
UC Davis	✔			✔		✔	✔
UCLA	✔	✔		✔			✔
UC Riverside	✔						✔
UC San Diego				✔			✔
Caltech					✔		✔
Carnegie Mellon	✔						✔
Fairfield		✔					
Fermilab	✔	✔		✔	✔	✔	✔
Florida	✔						✔
Florida State		✔					
Florida State/SCRI						✔	✔
Iowa		✔		✔			
Iowa State		✔		✔			
Livermore	✔				✔	✔	✔
Los Alamos						✔	
Maryland		✔					✔
Minnesota		✔			✔		
MIT	✔			✔			
Mississippi		✔		✔		✔	
SUNY Stony Brook	✔						✔
Northwestern						✔	
Ohio State	✔			✔			
Princeton					✔		
Purdue	✔	✔				✔	
Rice	✔					✔	✔
Rochester		✔					
UT Dallas	✔						
Texas Tech		✔				✔	
Wisconsin	✔			✔			✔

In addition to these scientific responsibilities, US personnel play a significant role in CMS management positions, as can be seen in the CMS organizational structure diagrams given in Chapter 20 of the CMS Technical Proposal[3].

2 Project Description

The NSF-supported groups in CMS are responsible for several major subsystem projects. Some of these involve close collaboration with other non-NSF groups. Some are the sole responsibility of NSF groups. In this section we review each of these subsystem projects that rely on the specific responsibilities and the unique expertise of the NSF groups in CMS.

2.1 Endcap Muon Alignment System

NSF groups involved: **Northeastern University**

One of the main goals of CMS is to determine muon momenta with high precision. The muon detector cannot perform this task unless the locations of its elements are known accurately and monitored continuously. Moreover, in order to obtain the best possible precision, information from the muon detector has to be combined with information from the central tracker. An elaborate alignment/position monitoring system has been designed to accomplish this. It consists of three subsystems:

- The Link System. It transfers the tracker coordinates (r, z, ϕ) from the central tracker to reference points (linking points) placed at both ends of the muon barrel wheels.
- The Barrel System. It accomplishes the alignment of the barrel muon detector elements with respect to each other and the linking points.
- The Forward System. It accomplishes the alignment of the forward muon detector elements with respect to each other and the linking points.

The conceptual design and the present status of the work on the muon alignment and monitoring system are reviewed in a recent progress report[4].

The Northeastern University group participating in EMU (J. Moromisato, P. Hanlet, E. von Goeler, D. Wood and T. Yasuda) has extensive experience with muon systems, most recently at SMC and DØ. The group has recently accepted the responsibility, and will use their expertise to provide EMU with a complete Forward Alignment System. The system determines the location of the endcap muon stations (MF1 through MF4) and, relates them to the tracker coordinates, i.e. the linking points. Conceptually, there are three steps:

- Alignment of the six planes in each muon module with respect to each other.
- Alignment of the muon modules within a station.
- Alignment of the stations with the CMS linking points.

In order to degrade the transverse momentum resolution by less than 15% over the whole $p_t - \eta$ range, the precision necessary is as follows (given for the extreme stations MF1 and MF4):

Coordinate	MF1 precision (μm)	MF4 precision (μm)
rϕ	50	100
r	500	1000
z	500	1000
Total bend plane error	55	110

Since the endcap chambers are mounted on the magnet return yoke, a significant amount of motion is expected. The z motion may be of order 5 mm; the ϕ and r motion should be less. It is not enough to establish the locations of the muon chambers during mounting; they have to be monitored continously.

The forward system's task is to ensure proper alignment and monitoring of the approximately 600 muon chamber modules in stations MF1 to MF4, mounted on the endcaps. Optical straight lines will run parallel to the z axis, in six planes (separated by approximately 60 degrees in ϕ) along the outer perimeter of the detector. They allow transfer of the link point coordinates to local reference points (connecting points) distributed on the endcaps. This transfer requires combinations of 'straightness' systems and 'distance' systems. A straightness system is an alignment tool able to measure the distance of points from a straight line. The r and ϕ coordinates are transferred this way. A distance system measures the distance between two points. The z coordinates will be transferred by distance systems to the connecting points and ultimately to the chambers.

Position sensing across each station, and tie-in with the outer connecting points is provided by multipoint straightness monitors (radial laser beam devices in conjunction with transparent photosensors). Fiducials on the chamber modules are tied to the local coordinates by a combination of proximity sensors and optical position sensors. Additionally, tracks will be used for both local and global r, ϕ measurement in the ϕ overlap region.

Important components of the alignment system have been used successfully in other experiments. However the difficult environment of the LHC requires a large amount of R&D during the next two years, prior to the design and construction of the final system.

2.2 Hadron Calorimeter Readout

NSF groups involved: **University of Illinois, Chicago**
University of Notre Dame
Virginia Polytechnic Institute and State University

The basic functions of the CMS calorimeter systems are to identify electrons and photons and to measure their energies (in conjunction with the tracking system), to measure the energies and directions of particle jets, and to provide hermetic coverage for measuring missing transverse energy. The central pseudorapidity range ($|\eta| < 3.0$) is covered by the barrel and endcap calorimeter system (HB, HF and ECAL), while the very forward region ($3.0 < |\eta| < 5.0$) is covered by the very forward calorimeter system (HV). The barrel and endcap calorimeters sit inside the 4 Tesla field of the CMS solenoid and hence are necessarily fashioned out of non-magnetic material (copper and stainless steel). The barrel hadron calorimeter inside the solenoid is relatively thin. To ensure adequate sampling depth for the entire $|\eta| < 3.0$ region a late hadron shower detection system is installed outside the solenoid coil utilizing the iron absorber of the muon system as part of the hadron calorimeter "late hadron shower detector". The active elements of the central hadron calorimeter are 4mm thick plastic scintillator tiles with wavelength-shifting (WLS) fiber readout [5]. The active elements were pioneered by CDF [6] and SDC [7].

The Hadron Calorimeter Design

Globally, the hadron calorimeter can be considered in two pieces: (a) a central calorimeter ($|\eta| < 3.0$) in which we require excellent jet identification and excellent single particle and jet resolution (HB/HF); and, (b) a forward/backward calorimeter ($3.0 < |\eta| < 5.0$) with modest hadron energy resolution but with good jet identification capability (HV). The forward calorimeter is physically separated from the central calorimeter, its front face being located at $\pm$ 11.0 m from the interaction point.

The central calorimeter is divided into a central barrel and two endcap calorimeter sections. The central barrel is divided into two half sections, each half section being inserted from either end of the barrel cryostat of the superconducting solenoid hung from rails in the median plane. Copper has been chosen as the absorber material because it has a shorter interaction length than steel, allowing an additional interaction length of material to be placed inside the coil.

Optical System

The hadron calorimeter will consist of a large number of towers ($\sim$ 3400). Inside the coil, each tower will have 19 layers of scintillator tiles grouped into 2 samplings in depth (HB1/HB2). Outside the coil cryostat, an additional two sampling layers of scintillator will be installed (HB3) around the muon absorber.

Multi-fiber optical connectors were developed by the CDF collaboration [6]. These connectors allow the optical signals to be treated similarly to electrical signals. The scintillator tile trays can be quickly connected and disconnected to multi-fiber optical cables (cf. multi-conductor electrical cables). The optical connectors are made via precision injection molding of mechanically stable plastic. In this manner, all connectors are identical, and there is no need for pair-matching of the connectors. The reproducibility of the optical connector transmission for many make/break operations has been measured to be 0.6% with a mean transmission of 83% for a single fiber, and an overall variation of $\sim$ 2 to 3 % for all fibers in the connector.

Photodetectors

The HB/HF photodetectors, which convert the optical signal from the fiber bundles corresponding to a tower, are required to have a linear dynamic range of 10^5 and operate in a uniform 4 T magnetic field. For calibration purposes, the detectors must have the capability of measuring the signal generated by a radioactive source as a DC current to a precision of 1%. In addition, the photodetectors are located inside the detector, adjacent to HB or HF itself, where service access is infrequent, thus placing an additional requirement on the mean time to failure. Progress is being made on the development of two types of proximity focused hybrid photodetectors (HPD) that can operate in magnetic fields and still provide gains of a few 1000.

The HPD has been chosen as the HB/HF baseline. Several manufacturers are under consideration (DEP and Hamamatsu).

Several channels of the CMS HCAL prototype module were instrumented with DEP HPDs during 1995 test beam work. This module was exposed to muons, pions and electrons. Separation of muons from electronics pedestal was possible, while good linearity for both pions and electrons was observed for the energy range tested [8].

Front-End Electronics

The electronic readout system of HCAL will probably be based on the same readout system as selected for ECAL; at present this is the CERN FERMI system [9]. The physics requires an ADC with a dynamic range of 20 MeV to 2 TeV. This dynamic range requirement is similar to that of the ECAL and will allow the HCAL group to profit from the adaptation of the FERMI system for ECAL.

The photodetectors and associated HV supplies, as well as their preamplifiers would reside close to the HCAL detector itself, distributed around the outer radius of the $|\eta| = 1.5$ transition region from barrel to endcap. They would be attached to either the barrel or endcap and would be able to travel along with their own subdetector. The signals from the preamplifiers would be routed out of the detector through the standard cable paths to electronics racks. In these racks would reside the FERMI system with its interfaces to the trigger and the event builder.

The HCAL electronics can thus be divided into the front-end amplification (linear 16-bit range, 40 MHz, 2000 electron r.m.s. noise), range compression, ADC and readout systems followed by Level-1 and Level-2 trigger Digital Signal Processors. High Voltage, Low Voltage and Slow Control systems and monitors are also required.

The NSF contribution

There are three NSF funded US institutes working on the CMS HCAL:

- The University of Illinois, Chicago (M. Adams, M. Chung and J. Solomon) is presently involved in the DØ experiment and is designing optical connectors and readout for the Scintillating Fiber Tracker Upgrade of that experiment.

- University of Notre Dame (R. Ruchti, B. Baumbaugh, J. Bishop, N. Biswas, J. Warchol and M. Wayne) is involved in the design and realization of the Scintillating Fiber Tracker Upgrade of the DØ experiment. This group was also part of the design team for the Scintillating Fiber Tracker for the SDC experiment at the SSC and made major contributions in photodetector work for that design project.

- Virginia Polytechnic Institute and State University (L. Mo, K. Blankenship, B. Lu and T.A. Nunamaker) is involved in the ZEUS experiment at HERA at DESY, and is responsible for the development of photodetector readout for that experiment. This VPI group worked on the SDC tile calorimeter, concentrating on photodetectors and their readout for that experiment as well. They have also contributed to electronics development on many experiments.

These NSF funded institutes are involved in the realization of the optical readout of the scintillator tiles, the front-end electronics and associated housing and power supplies, the readout electronics and the HCAL digital interfaces to the DAQ and Trigger. They will work with their colleagues from Fermilab, Minnesota, Rochester, UCLA and other CMS institutes to design, construct and implement this system according to the CMS HCAL requirements and specifications as set out in the CMS HCAL Technical Design Report (TDR). As CMS HCAL collaborators they will participate in the writing of the appropriate sections of the TDR document and, in particular, the list of requirements and specifications.

It is proposed that the NSF has fiscal reponsibility for optical readout, photodetector and electronics systems. The NSF support will be concentrated in the endcap calorimeters (HF).

2.3 Luminosity Monitoring System

NSF groups involved: **University of Nebraska**
University of California, Los Angeles

The NSF-funded groups at Nebraska (G. Snow, S. Atkins, W. Campbell, D. Claes, M. Hu and C. Lundstedt) and UCLA (P. Schlein, S. Erhan and J. Zweizig) are requesting support for work on the CMS luminosity measurement. The CMS luminosity subgroup was formed in 1994 with representatives from several associated areas within CMS. The aim of the project is to provide a detector subsystem which is capable of providing precise ($\sigma_{Lum} \leq 5\%$) luminosity measurements for determining cross sections [10]. It will also provide the LHC machine with real-time feedback of the luminosity and beam conditions in the CMS area.

The importance attributed by the CMS collaboration to the luminosity project is indicated by the fact that G. Snow is an observer-member of the CMS Technical Board. However, the scope of the project will allow it to be carried out by a relatively small number of CMS physicists, students and technicians, given appropriate input from and coordination with LHC accelerator physicists.

An introduction to the luminosity measurement is given in Section 13.3 of the CMS Technical Proposal (TP)[3]. Techniques for determining the absolute and relative luminosities for each of the 2835 bunch crossings are also outlined in this section of the TP. The luminosity measurement and beam-condition monitoring will be based on three types of detector elements: the dedicated luminosity counters, the Roman pot detectors, and the beam-scraping monitors. The baseline designs for these elements are described below. Results of simulation studies and prototype tests may influence a choice of particular detector technology, but the principles of the three detector elements should remain fixed.

The detectors proposed for the luminosity and beam-condition monitoring will also prove useful for triggering and important physics measurements, in particular, elastic and hard-diffractive scattering. The latter physics topic is studied by tagging hard-scattering events in the CMS detector with beam-like final-state protons in one or both arms (called single diffraction and double-pomeron-exchange, respectively). Such measurements were first made by experiment UA8 at CERN, which tagged events in the UA2 detector with protons detected in Roman pot spectrometers. Currently, such measurements are being carried out (or in the planning stage) by the ZEUS and H1 experiments at DESY and by the CDF and DØ experiments at Fermilab.

It should be noted that both single diffraction and the double-pomeron-exchange processes will likely only be accessible during relatively low-luminosity running of the LHC.

The UCLA group plans to work together with the Nebraska group and will contribute its experience with the UA8 experiment to the CMS effort.

Dedicated Luminosity Counters

The dedicated luminosity counters will be two arrays of fine-grained, thin scintillator tiles, one on each side of the interaction region, covering the pseudorapidity range of approximately $4 <| \eta |< 5$. The granularity of the arrays is coupled to their longitudinal placement; however, arrays of fewer than 100 elements each are foreseen. Both hexagonal tiles and concentric half-rings are being considered for the counter layout. The light read-out scheme, presently based on embedded wavelength-shifting fibers carrying light to remote phototubes, is under study and will influence the final counter geometry. The utility of a laser-based or source-based calibration/pulser system is also under study.

The luminosity counters are required to have the following characteristics: good and well-determined acceptance for detecting hard-core scattering, very tight (i.e. sub-ns) timing resolution in the high-rate environment, high efficiency for single minimum ionizing particles, a large dynamic range and radiation hardness.

Hits in the arrays will be used to count the number of front-back coincident events, the number of front-only or back-only events, and the number of neither-side-hit events for each of the bunch crossings. These rates, the acceptances of the counters for hard-core scattering, single diffractive and double-pomeron-exchange scattering, and measured (by CMS and other experiments) cross sections for these processes at $\sqrt{s} = 14$ TeV will combine to yield the luminosity for each bunch crossing. The counters will be used for several other purposes. They will monitor interaction rates during separated beam scans (Van der Meer method [11]), which will aid in the absolute luminosity calibration. They will provide real-time accelerator diagnostics during scraping, beam tuning, and throughout a physics store (run). The counters will also be able to provide a single/multiple interaction flag available for triggering, especially during low-luminosity running. The timing information from the luminosity counters will be useful in confirming multiple vertices found off-line by the inner tracker.

During the first few years of LHC running, the anticipated luminosity will be a factor of 10 to 100 lower than the design luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, although the number of bunches will be the design value of 2835. During these years and other planned low-luminosity running, the precise timing of the luminosity counters will allow them to provide an "intelligent prescale" where bunch crossings with a single pp interaction can be selected. Rates in the luminosity counters during low luminosity running will calibrate other luminosity tools for transfer to higher luminosities. Other tools include the tower firing-rates which will be accumulated by the Level-1 calorimeter trigger electronics and the rates of easily-identified and reconstructed physics processes. Rates for $W^{\pm}$, Z^0, and high–p_T J/ψ production are candidate physics processes for luminosity monitoring.

An important step in calibrating the luminosity counters will be to run the LHC at a lower center-of-mass energy where the total pp cross section and its components (hard-core, elastic, single-diffractive, ...) have been accurately measured. For example, it will be possible to run the LHC as low as 2 TeV, albeit with reduced luminosity, so that the luminosity calibration can be cross checked with the measured cross sections at the Tevatron.

Roman Pot Detectors

The luminosity group proposes to design and install the only "extreme forward" detectors in CMS, located in Roman pots and placed symmetrically at large distances (> 100 m) from the interaction region. The Roman pot detectors are designed to measure the tracks of particles which emerge from a *pp* interaction at extremely small angles with respect to the beam. The detection of recoil protons at low-t will be essential for measurements and monitoring of elastic and diffractive cross sections at $\sqrt{s} = 14$ TeV, which will play an important role in the luminosity measurement.

Tracking such small-angle particles calls for detectors which can be moved close to the circulating beams (in the machine vacuum) when stable beam conditions are established. A system of at least 6 pots are proposed, 3 on each side of the interaction region. Early studies show that the existing accelerator beam optics in the vicinity of the CMS detector will displace scattered protons with momentum loss in the range $2 \times 10^{-3} < \Delta p/p < 0.1$ outside the envelope of the unscattered beams [12]. At a distance of ≈ 300 m on either side of the interaction point, detectors in Roman pots which are positioned $10\,\sigma$ from the beam axis will intercept scattered protons in the above range.

Roman pot detectors and their associated mechanics (pot movement, position monitoring, vacuum interface, interlocks, ...) have already been used widely at CERN, DESY and Fermilab. Thus, we anticipate using standard technologies. Detectors based on scintillating fibers and silicon pixel devices are being studied. The final design of this system will no doubt be influenced by the experiences of the CDF and DØ experiments which will be using the latest state-of-the-art Roman pot detectors during Run 2 of the Tevatron.

Due to the large distance of the Roman pots from the CMS detector, it is foreseen to transmit digitized information from the pots to the central DAQ. The CMS Slow Controls group is involved in various mechanical and control aspects of the proposed Roman pots.

Beam-Scraping Monitors

The luminosity subgroup has responsibility for implementing a system of detectors surrounding the beam pipe in the vicinity of the CMS detector for monitoring the beam condition. These detectors will be most useful during beam tuning and scraping. A secondary purpose is to monitor and tag background events from beam-gas and beam halo interactions, made possible by the comparison of particle arrival times at appropriately spaced positions.

2.4 High Level Trigger and Data Acquisition System

NSF groups involved: **University of California, Los Angeles**
University of California, San Diego
Northeastern University

At the LHC design luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, an average of 20 inelastic interactions will occur every 25 ns, the bunch crossing time. The goal of the CMS Trigger/DAQ system is to record the most interesting collisions out of the $\mathcal{O}(10^9)$ interactions per second at the LHC. This will be achieved by a three-level trigger system.

The Level-1 Trigger System aims to reduce the input interaction rate to a rate of 100 kHz. At this point, one physics event is contained in about 1000 front-end buffers which must be transported to a single location for further physics analysis (the "event building" process). This is achieved using a switching network to connect these buffers to a farm of processors. These processors run dedicated physics algorithms to further select the most interesting events (the "event filtering" process). Given the limitations of offline mass storage and processing, the final output of the experiment should not exceed 100 Hz.

CMS plans to perform the event-building and filtering processes in two steps: the "virtual Level-2 Trigger" and the "Level-3 Trigger". For each event accepted by the Level-1 Trigger, only a small fraction of the detector output is transported upstream into a single processor which is capable of making a refined analysis of the event based on this limited information. This is the "Level-2" decision on the event. If the event is accepted by Level-2, the rest of the event is transported to the same processor for full analysis and final decision ("Level-3") on whether to output the event to mass storage.

Level-2 is referred to as "virtual" because it is a software task running on the same farm of processors which analyzes the full event at Level-3; *i.e.* it does not use special-purpose hardware processors. The choice of a "virtual Level-2 Trigger" is driven by its obvious flexibility and by the realization that the additional event building needed to provide input to a hardware level-2 trigger is more expensive than memory needed to cope with the latencies associated with a processor-based Level-2 system. Preliminary estimates indicate that a set of 1000 processors, of $10^3 - 10^4$ Mips each, is required for the Level-2 and Level-3 farm.

US role in CMS DAQ

Several US institutions on CMS are currently participating in the design and development of the entire DAQ system. In particular, US institutions are working on:

- the Readout Dual Port Memories (RDPM), including the links to the switch;
- the Control and Status System for the readout crates;
- the Switch Farm Interface (SFI);
- the Event Flow Control system;
- the High Level Trigger system.

The US institutions will construct one-half of the full DAQ system, including RDPMs, SFIs and Control and Status Systems, together with the full Event Flow Control System. They will also participate in the installation and integration of the system into CMS. Current plans in CMS call for the completion of testing a prototype system 18 months prior to installation. While prototypes will be constructed with both industrial and lab participation, it is expected that the final construction will be mainly industrial. The labs will have to assure quality control, provide software, and participate in the installation at CERN. We expect that our European colleagues will bear the majority of the installation and maintenance task. Nevertheless, a significant US effort will be required to assure that the US components are integrated smoothly into the experiment.

NSF groups on Trigger/DAQ
There are currently three NSF-funded institutions active on the CMS Trigger/DAQ system:

- **The UCLA NSF group** (P. Schlein, S. Erhan and J. Zweizig) intends to work on the CMS trigger and DAQ project. Presently, members of the group play leading roles in these areas in the HERA-B experiment. The event rates and bunch structure at HERA are similar to those at the LHC, so many problems which will be encountered by CMS will first be faced by HERA-B. The expertise and experience gained by this group on HERA-B should greatly benefit the US CMS Trigger/DAQ effort.

- **The UCSD NSF group** (H. Paar, G. Masek and M. Sivertz) is in close collaboration with the DOE group from the same institution. They are expected to contribute to the current program of work i.e. the RDPM and SFI development.

- **The Northeastern group** (L. Taylor, G. Alverson, T. Paul and J. Swain) is expected to make major contributions to the High Level Triggers. The group has extensive experience in the installation and management of large clusters of processors (workstations) for the L3 experiment and are already involved in numerous CMS offline computing activities, as described below. They will capitalize on this experience to take a leading role in the design and implementation of the Level-2 and Level-3 Trigger systems.

In this document we propose that the NSF-funded institutions on the CMS DAQ project acquire full responsibility for the development of (a) the Control and Status system (RCS) for the readout crates and (b) the Readout Data Links (RDL) from the RDPMs to the switch. All of these groups are also expected to participate in the development of the physics algorithms for the High Level Triggers.

Both subsystems (the RCS and RDL) are integral parts of the basic readout unit (RDPM) in the CMS DAQ. The development of the RDPM (i.e. the input to the switch) and the SFI (i.e. the equivalent module for data output from the switch), represent a key contribution of the US to the CMS DAQ system. With this suggested sharing of responsibilities, we expect to establish a close collaboration between the DOE and NSF-funded institutions. We expect to share development platforms across institutions. In addition, this breakdown is quite modular, in that it allows the development of the RCS-RDL subsystems in parallel with the RDPM-SFI system. We expect that this plan will maximize our ability to independently address design details while maintaining our ability to address the CMS DAQ Readout Crate as a full system, developed in the US.

It is also expected that all three institutions will participate in the design and implementation of the software algorithms running on the Level-2/Level-3 processor farm. The software algorithms running on the processor farm will be based on those used by the offline reconstruction programs. At one extreme, the two programs will be identical. At another extreme, the high rates expected will result in the creation of dedicated fast algorithms with little resemblance to the offline program. A crucial feature of this software system is that, unlike the equivalent systems of previous experiments, it must be robust and reliable essentially from the beginning of the first data-taking period.

2.5 Electromagnetic Calorimeter Readout

NSF groups involved: **Northeastern University**

The CMS electromagnetic calorimeter must be able to measure electrons and photons with sufficient precision so as not to compromise physics performance. Powerful isolation cuts and two-shower separation capability are required to eliminate the background from jets and single π^0's. A high resolution, good lateral granularity crystal calorimeter surrounding the inner tracking volume inside the coil is the chosen design. The US group responsibilities in ECAL are directed primarily towards the overall front-end electronics and the photodetectors, with some efforts aimed at crystal surface treatment and other processing techniques.

Lead tungstate ($PbWO_4$) crystals have been manufactured for which the light output, though modest, remains stable after a small ($\sim$10%) reduction caused by low radiation doses has been accounted for. Extensive efforts are underway to reduce or remove this low dose degradation. In parallel with this work, the collaboration is working with Chinese and Russian crystal manufacturers to establish the optimum procedure for mass-production of these crystals.

The Northeastern University group (S. Reucroft, Y. Musienko, D. Ruuska and J. Swain) has extensive experience with optical transducers and it plans to concentrate its ECAL efforts on the readout devices for these crystals.

The development of a stable and reliable photodetector which can operate in the CMS environment requires a systematic approach in which the collaborating institutions will work closely with the manufacturers. The avalanche photodiode (APD) is a device which has not yet been used in any large-scale high-energy physics experiment, but which has been used extensively for the past 20 years by the defense industry. It has characteristics which make it very suitable for the CMS calorimeter readout. It is a small, sturdy, robust, efficient and relatively inexpensive device [13]. Several companies manufacture APDs. The Northeastern University group has developed significant expertise working with APDs from EG&G, RMD and API [14],[15],[16], and plans to extend this to devices made by Hamamatsu. In particular, the group has extensive experience in studies of radiation hardness of APD's, a matter of great importance in the harsh CMS environment. These studies have played, and continue to play, a key role in the understanding of device performance in the intense CMS neutron fields. Indeed, the recently identified problem of radiation damage induced dark current increase and the associated understanding of the problem came directly from the Northeastern/Minnesota work at Oak Ridge National Lab [15],[16]. This work could have enormous impact on the ultimate design of ECAL.

The Northeastern group's experience relevant to the ECAL is not limited to APD's but also includes the design and testing of a scintillating-fiber readout system for the SDC tracker [17]. The group's expertise is being merged with that of the University of Minnesota group and the Fermilab group to provide a significant percentage of the entire ECAL readout system.

In particular, the Northeastern group, in collaboration with the University of Minnesota group, will continue to work closely with the various APD manufacturers in order to guide them towards the manufacture of useful devices for our purposes. Project costs will involve purchasing, testing and performing quality control tests of the large quantity of APD's needed for the ECAL readout. These two institutions will provide a third of the APD's required by the CMS experiment and complementary centers will be established for quality control and testing, including radiation hardness, of the purchased APD's according to CMS requirements. We expect excellent opportunities to involve students in these activities; in fact it is noteworthy that most of our APD radiation damage studies were carried out by a Northeastern graduate student.

2.6 Forward Pixel Tracking System

NSF groups involved: **Johns Hopkins University**

US CMS has full responsibility for the forward pixel system. It has six disks of pixels with three at each end ($z = \pm 34$, ± 54, ± 69 cm) covering from r = 7.5 to 15.0 cm, with a total of 23 million pixels. The two inner disks ($z = \pm 34$ cm) have minidisks attached to them, extending the coverage to r = 4.5 cm. The support we request from the NSF is for 40% of the forward pixel system. The pixels are crucial elements of tracking because of their innermost position. They are also important from the beginning of the data taking, because the minidisks are required for the B-physics program during the first two years of operation when luminosity is low. Later, when LHC goes to its full luminosity, the minidisks will be removed.

The details of the detector have been reported in the CMS Technical Proposal [3]. We will describe below only the Johns Hopkins group (C-Y. Chien, B. Barnett, D. Gerdes, G. Hu and A. Pevsner) responsibilities. These include all the forward pixel detector diode arrays, Local Communication Chips (LCC), connection to the VME via the kapton cable, optical fiber and Optical Transmitter/Receiver (OTR). The tasks include the R&D, design, fabrication, and testing of these components. These tasks were selected based on the experience and expertise we acquired from our work on L3 [21] and CDF [22], and the R&D work for SDC [18] [19] [20] and at CERN [23] where we dealt with the development of silicon detectors, radiation damage, kapton cables, and signal handling extensively.

Pixel disks are covered by pixel detector array modules. In the current design each module has 16K pixels with four readout chips bump-bonded above it, and with a kapton cable connected on one edge. The detector array module provides signal and power bussing from the bump-bonded readout chips and LCC to wire bond pads at one edge of the detector for the kapton cable.

The overall system operates as follows. When a charged particle passes through the pixel (covering an area of 1/64 mm^2), an electric signal is generated and passed through the bump-bond to the corresponding element of the readout chip attached above where each signal is amplified and processed. Signals above threshold are buffered and time stamped. When the readout chip receives the level-1 trigger, it accepts signals and sends out information corresponding to the associated beam crossing, and clears the remainder. The LCC on the detector module is the interface between the readout chips and an OTR. The OTR is connected by a kapton cable to the detector modules on one end; and to a remote VME card in the DAQ system via optical fibers on the other end.

The requirement for the pixels is to provide 15 μm and 90 μm resolution in the $r\phi$ and r directions respectively. We will exceed this resolution in r to provide better resolution in z. However, it is also required that pixels can function in partially depleted mode after being exposed to a fluence of 10^{15} protons/cm^2, which is equivalent to several years of operation at LHC at full luminosity for the inner pixels. This imposes a severe constraint on the design of the pixel array, requiring much R&D work on a large number of issues.

The strategy for the tracking effort has been to complete an optimal design on the geometry so that the mechanical and cooling design work can proceed with other parts of CMS; at the same time we can proceed on the detailed R&D so that an initial design can be completed at the end of 1997 for the Technical Design Report (TDR). The tasks to be performed by the Johns Hopkins group are as follows:

Simulation and Software

We have used a package of fast simulation programs to calculate the resolutions of different pixel geometries. This will be finalized in late 1996. Then work will continue to include a complete simulation package into the overall tracking software.

Diode Arrays

We must develop a pixel design satisfying all requirements. We need to answer detailed questions such as: effects due to radiation damage, pixel thickness vs. depletion voltage, bulk type, readout isolation, cross talk, guard structures, charge sharing, readout pad bump-bonding reliability, yields, and production cost, etc. To coordinate with the development of the readout chips and other components, it will be developed in four stages:

- A 16×16 pixel array with fan-out readout to test geometry and radiation hardening (1996-97). The 16×16 arrays have been fabricated and received. We have also obtained readout electronics using VA2 chips. A beam test will be carried out on four 16×16 pixel arrays at CERN in Summer 1996 using the beam telescope system and DAQ we developed at CERN. The pixel radiation test will be completed in Spring 1997. Tests will begin at the FNAL booster in Fall, 1996. They will be radiated to 10^{15} p/cm^2, then retested in a beam. This process will go through several iterations to reach the full fluence required.

- A 24×32-pixel array to test read-out design (1997). This design will be based on the radiation test results from the 16×16 arrays, and the optimization from Monte Carlo simulation. It will be completed in 1997 and tested with pixel readout chips from UC Davis and PSI.

- A multi-chip array to test module assembly and communication (1998).

- A full size prototype module in 1999.

Signal Routing

- *Local Communication Chips (LCC)*: The LCC handles communication between the pixel readout chips and the OTR. Both of them are still evolving. So there will be several iterations in 1997 before a prototype is completed for the Technical Design Report (TDR). A multi-chip prototype will be produced in 1998. The final design will wait for the completion of the design of readout chips and OTR, followed by production afterwards.

- *Kapton Cable*: A low mass, high reliability connection with kapton cables will be used to connect detector array modules to power supplies and the OTR.
- *Optical Transmitter/Receiver (OTR) and Optical Fiber*: The design and fabrication of the frontend electronics of all CMS subdetectors take on a common approach by the same group of people, except the pixels – because of its special nature and the enormous number of channels involved. We will work with Imperial College and CERN to test the common design of the OTR and fiber and develop necessary modifications for the pixels.

2.7 Computing and Software

Computing software and hardware are of paramount importance to CMS. As both the detectors and events recorded in high energy physics experiments have become more and more complex, the computing infrastructure has become a major detector subsystem in its own right. Without appropriate software investment, the detector hardware design will not be optimized, and the potential of the detector to do competitive physics will be severely compromised.

The CMS computing project concerns itself with tasks which are common to all the detector subsystems or which are needed by all individual members of the collaboration. There is also a great deal of detector-specific software required; this, however, is considered as part of the appropriate subdetector project.

Two NSF-supported groups have already started making major contributions to the area of Computing and Software. These are Northeastern University (L. Taylor, G. Alverson, T. Paul and J. Swain) and Johns Hopkins University (A. Gougas et al). It is anticipated that eventually all NSF groups will become involved. In this proposal we are not requesting specific project funds for computing and software. Rather, we anticipate that funding for this will be included in the Operations and Pre-Operations costs, and in future base-budgets of individual groups.

CMS is currently in the process of writing a "Computing Technical Proposal" which will be submitted to the LHC Computing Board in December of 1996. The Northeastern group is taking an active role in the preparation of this document, for which L. Taylor is editor.

In the following, we note the other main projects in which the Northeastern group has taken a leading role. It is worth emphasising that these form a natural extension of NSF-funded work on L3, where the group played a critical role in the offline computing over a period of several years and wrote the definitive document on the use of computing resources[25]:

- The Northeastern group is responsible for providing the standard CMS simulated physics event samples and for the code used to generate them. The group has written the CMKIN[27] package which provides a uniform interface to distinct event generation programs, such as Pythia and ISAJET, and a standard output event format which is read by the CMS simulation program, CMSIM.

- The group is actively involved in the development of CMSIM. They are responsible for the general utility routines, and have designed and implemented the I/O, file-handling, and database package, known as CMDB[26].

- The critical need for large amounts of CPU power for the generation of Monte Carlo simulated events has prompted the group to investigate two complementary solutions involving a) dedicated farms of low-end, large CPU but modest I/O computers and b) the exploitation of the spare CPU power of under-utilized CMS computers. This evaluation work is being carried out with support from Hewlett-Packard and in the context of the CERN Research and Development project, known as HEP PC[28].

- Northeastern is responsible for the detector and event visualization program, known as CMSCAN[29]. CMSCAN is an invaluable tool for optimizing the design of the detector and its sensitivity to interesting physics processes. Using CMSCAN, a CMS event picture library has been made available on the WWW.

- Ensuring the high quality of the CMS software is of paramount importance, especially since offline reconstruction algorithms will be used in the Level-2/3 trigger farm. The Northeastern group has taken the lead by defining the CMS coding standards[30]. They have implemented an automatic code-quality checker for the standard CMS code, the results of which are available to distributed collaborators via WWW.

The Johns Hopkins group has started developing algorithms to be used with the GEANT package in order to: a) change the dimensions of arbitrary detector shapes, controlling for their boundaries in a user-friendly (graphic) way. b) calculate the corresponding number of channels, after each geometry change by either readjusting the pitch or by getting input from the user c) calculate the corresponding material in terms of radiation length

The code is being developed primarily for the geometry optimization of the pixel and microstrip silicon detectors. It can find application with other subdetectors of CMS.

2.8 Education Integration Issues

The CMS-NSF groups will continue to include a strong educational component as part of their research program. No funding for this is being sought in this proposal. Other proposals either already have been, or will be submitted. This section is for information only.

Physics Graduate Students

We will continue to educate the traditional Ph.D.-bound student in research techniques and procedures. Eventually students will receive their Ph.D.'s on CMS data, but due to the long construction period, the early years will be used to give hands-on design and construction experience to students who otherwise could spend their entire graduate careers doing only analysis. This is also true for MS students who take the thesis option.

Physics Undergraduate Students/ Co-op Students

Most CMS-NSF groups also include undergraduate students in their research programs, and this is anticipated to continue in CMS. In particular, the Northeastern group gives out undergraduate co-op positions for students to spend one or more quarters at a lab, normally either Fermilab or CERN. Although not primarily intended as a feeder program for graduate schools, a number of Northeastern co-ops have gone on to study physics at other prestigious schools. Notre Dame has maintained an NSF/REU summer program for college juniors which has been in place for better part of a decade. Each year the Notre Dame group has had the active and effective participation of these students in several experiments at Fermilab. Beginning in Summer, 1996 this will also involve CMS.

Science Alive The Notre Dame group has participated in "Science Alive", an outreach program in the South Bend community, to interest primary and secondary school children in science, physics, and high energy physics.

Joint Education-Physics Program

Education programs have felt an increasing pressure to include not only pedagogical studies, but also to have their participants be experts in some particular field. We are in the process of submitting a proposal for a joint program that would include work on CMS as part of a physics-education degree for high-school teacher training.

MInDLab

We also have a proposal under consideration by the DOE SBIR program for a Mobile Interactive Detector Laboratory (MInDLab). The proposal was submitted by a small company based in North Carolina (Quantum Research Services, Inc.) and involves several CMS physicists as consultants. MInDLab would bring sophisticated interactive experiments to schools lacking such facilities. Of course, exhibits on CMS as an example of a state-of-the-art experiment would be included.

World Wide Web

The World Wide Web was developed at CERN and is heavily used within CMS to facilitate the communication of information between distributed collaborators. It is also an ideal medium for presenting HEP to the general public, and in particular to secondary schools and undergraduate physics departments throughout the US. We are already studying the use of Java to provide interactive educational tools on the Web, one example being a simplified version of the CMS event display program.

Fermilab Education Program The Fermilab commitment to enhancing mathematics and science education and stimulating science literacy has four major objectives: strengthening mathematics and science education throughout the system, especially in the early years; increasing the number of teachers with a substantive background in science and mathematics via e.g. staff development opportunities; increasing the number of young students, especially girls and members of minorities, who retain their curiosity about the natural world as they grow up; increasing the number of undergraduate and graduate students, especially women and members of minorities, who complete degrees in science, particularly particle physics, mathematics and technology. For more details, see the Fermilab Education web site [31].

3 Bibliography

[1] D. Green et al., "US Collaboration for the CMS Detector at the CERN LHC", Letter of Intent, September 8, 1995.

[2] D. Green et al., "US CMS Project Management Plan" (Draft), April 12, 1996.

[3] M. Della Negra et al., "CMS Technical Proposal", CERN LHCC/P1, December 1994. On WWW, see *ftp://cmsdoc.cern.ch/TPref/TP.html.*

[4] The Muon Alignment Group, "CMS Muon Alignment-Progress Report", CMS TN/96-050 (1996).

[5] V. I. Kryshkin and A. I. Ronzhin, NIM **247** (1986) 583.
M. G. Albrow, et al., NIM **256** 23 (1987).

[6] S. Aota, et al., "A Scintillating Tile/Fiber System for the CDF Plug Upgrade EM Calorimeter", CDF-2431, March 10, 1994

[7] "SDC Technical Design of a Detector to be operated at the Superconducting Super Collider", SDC-92-201, April 1, 1992

[8] P. Cushman, et al., "Multi-Pixel Hybrid Photodiode Tubes for the CMS Hadron Calorimeter", *Proceedings of International Conference on Photodetectors in HEP*, Baune, France, June 1996

[9] G. Goggi and B. Lofstedt, "Status Report on the FERMI Project" CERN/DRDC/94-17.

[10] I. Hinchliffe, "How well does SDC need to measure cross sections?", SSC-SDC report, June 1993.

[11] A. Morsch, "Luminosity, vertex distribution and the Van der Meer method", CERN AT Note, January 1993.

[12] K. Eggert and A. Morsch, "Leading proton detection in diffractive events for an LHC low-β insertion", CERN AT/94-09 (DI), LHC Note 289.

[13] R. J. McIntyre et al., "Properties of Avalanche Photodiodes", RCA Review, 1974.

[14] S. Reucroft et al., "Test of Advanced Photonix Inc. APD's in a Fast Neutron Flux", NEU Internal Report, 1993.

[15] S. Reucroft et al., "Neutron Irradiation Studies of Avalanche Photodiodes Using Californium-252", talk presented by J. Swain at the First Conference on New Developments in Photodetection in Beaune, France, June 1996 (and to appear in the proceedings to be published in NIM)

[16] S. Reucroft et al., "Neutron Irradiation Studies of Avalanche Photodiodes" Nucl. Instr. Meth. (1996).

[17] S. Reucroft et al., "Avalanche Photodiodes as Plastic Fiber Readout Devices", Rad. Phys. Chem. 42, 1993.

[18] T. Anticic *et al.*, "Spatial Resolution of Wedge Shaped Silicon Microstrip Detectors", Nucl. Instr. Meth. **A365** (1995) 70.

[19] B. Barnett *et al.*, "The Effect of Radiation on Silicon Microstrip Detectors with Variable Strip Pitch", JHU-HEP-95-120, submitted to Nucl. Instr. Meth A.

[20] J. Krizmanic *et al.*, "A 1060 nm Diode Laser System for Dynamically Probing Silicon Detectors", Nucl. Instr. Meth. **A374** (1996) 315.

[21] F. Beissel, *et al.*, "Construction and Performance of the L3 Central Tracking Detector", Nucl. Instr. Meth. **A332** (1993) 33.

[22] S. Chihangir *et al.*, "SVX: the New CDF Silicon Vertex Detector", Nucl. Instr. Meth. **A360** No. 1&2 (1995).

[23] W. Braunschweig *et al.*, "Beam Test Results on Si and GaAs Detectors with Length up to 64 cm", Nucl. Instr. Meth. **A366** (1995) 236.

[24] A. Gougas, private communication (1995).

[25] J. Swain and L. Taylor, "The L3 Computing Guide" (351 pages), L3 Internal Note and Northeastern Note NUB-3065, May 1993.

[26] L. Taylor, "Implementation of the CMDB file-based database system in CMSIM", CMS TN-95/171, November 1995.

[27] L. Taylor, "CMKIN - The CMS Kinematics Interface Package", CMS TN-96/099, July 1996.

[28] M. Delfino et al., "High Energy Physics Processing using Commodity Components (HEP PC)", CERN/LHCC/95-46, August 1995, (Proposal 61 to the LCRB, accepted and now operating as the RD47 project).

[29] L. Taylor, "CMSCAN – The CMS Event Display Program", Invited talk at HEPVIS 95, Fermilab, Illinois, August 1995.
L. Taylor, "Interactive Graphics for the CMS Experiment at the LHC", Invited talk at CHEP 95, Rio de Janeiro, September 1995.

[30] J. Swain and L. Taylor, "The CMS Fortran Standard", CMS TN-95/082, July 1995.

[31] On WWW, see *http://www-ed.fnal.gov/*

4 Biographical Data

The next few pages give brief biographical sketches of the Co-Principal Investigators and project contact persons. These are:

- Steve Reucroft, Northeastern University (ECAL Readout)
- Mark Adams, University of Illinois, Chicago (HCAL Readout)
- Chih-Yung Chien, Johns Hopkins University (Forward Pixel Tracking)
- Luke Mo, Virginia Polytechnic Institute and State University (HCAL Readout)
- Jorge Moromisato, Northeastern University (EMU Alignment)
- Hans Paar, University of California, San Diego (DAQ)
- Randy Ruchti, University of Notre Dame (HCAL Readout)
- Peter Schlein, University of California, Los Angeles (DAQ and Luminosity Monitor)
- Greg Snow, University of Nebraska (Luminosity Monitor)
- Lucas Taylor, Northeastern University (Computing/Software and High-Level Triggers)

5 Budget

5.1 Construction Summary

In this section, we present a summary of the cost of the construction for the NSF projects described above. This summary has been extracted from the overall cost estimates of the US portion of the CMS project as produced by the US CMS Management Board. In fact, since the Management Board has the ultimate responsibility for the assignment of monies to tasks it is not unlikely that the amounts in the table will be subject to fine-tuning before distribution to individual projects. This distribution will be administered via sub-contracts to the appropriate university groups. The larger context for this proposal and these construction costs is contained in the CMS Technical Proposal (CERN/LHCC 94-38) and in the US CMS Letter of Intent of September 1995 and the governance aspects are covered in the US CMS Project Management Plan.

A summary of the costs per subsystem is contained in the attached WBS which outlines the costs of the US CMS project. The specific NSF subset of the project is projected out in the second summary table.

5.2 Cost Profile of the Total Project

The table below shows the costs for the years between FY96 and FY05, inclusive. Details may change as experience is gained with different aspects of the project; this table gives a preliminary cost profile as presented to US CMS by the NSF. We have been advised that the profile amounts should be interpreted as FY96 dollars.

Preliminary US CMS Cost Profile. (All amounts in FY96 $M).

Fiscal Year	FY96	FY97	FY98	FY99	FY00	FY01	FY02	FY03	FY04	FY05	Total
NSF R&D	0.1	0.3	0.3	0.3							1.0
NSF Project				3.0	3.4	3.4	3.2	3.2	2.8		19.0
Total	0.1	0.3	0.3	3.3	3.4	3.4	3.2	3.2	2.8		20.0

US CMS Project Cost Estimate

WBS Number	Description	US Mfg M&S (K$)	US Mfg Labor (K$)	US EDIA (K$)	US Base Cost (K$)	US Cont (K$)	Total US Cost (K$)	DOE Request (K$)	NSF Request (K$)
Total US CMS Project Request								**148,418**	**20,032**
Escalation								20,911	
FY'96 R&D							2,400	2,300	100
US CMS Total Estimated Cost (FY'96 $s)		**84,819**	**11,384**	**22,717**	**118,919**	**26,220**	**145,139**	**125,207**	**19,932**
1	**Endcap Muon System**	**18,425**	**5,337**	**6,990**	**30,752**	**7,739**	**38,491**	**36,827**	**1,664**
1.1	Muon Measurement System	18,425	5,337	5,511	29,273	7,369	36,642	34,978	1,664
1.2	Endcap Iron Design	0	0	1,479	1,479	370	1,849	1,849	0
2	**Hadron Calorimeter**	**26,331**	**3,112**	**3,254**	**32,697**	**9,809**	**42,506**	**35,420**	**7,086**
2.1	Barrel Hadron Calorimeter	20,966	1,973	2,610	25,548	7,664	33,213	31,161	2,052
2.2	Endcap Hadron Calorimeter	3,196	587	90	3,873	1,162	5,035	0	5,035
2.3	Very Forward Calorimeter	2,169	552	554	3,276	983	4,259	4,259	0
3	**Trigger/Data Acquisition**	**9,736**	**454**	**3,804**	**13,994**	**4,019**	**18,013**	**16,155**	**1,858**
3.1	Endcap Muon Level 1 CSC Trigger	1,181	0	873	2,053	595	2,649	2,649	0
3.2	Calorimeter Level 1 Regional Trigger	3,018	0	1,465	4,482	1,300	5,782	5,782	0
3.3	Luminosity Monitor	345	42	48	435	87	522	0	522
3.4	Data Acquisition	5,193	412	1,419	7,024	2,037	9,061	7,724	1,336
4	**Electromagnetic Calorimeter**	**5,742**	**1,382**	**1,675**	**8,800**	**1,696**	**10,495**	**7,724**	**2,772**
4.1	Barrel Photodetectors	2,175	283	314	2,771	693	3,464	693	2,772
4.2	Very Front-End Electronics	2,835	451	922	4,208	717	4,925	4,925	0
4.3	Crystal Processing	176	270	291	737	72	809	809	0
4.4	Monitoring Light Source	556	379	148	1,083	214	1,297	1,297	0
5	**Tracking**	**2,346**	**1,099**	**1,915**	**5,360**	**2,144**	**7,503**	**4,134**	**3,369**
5.1	Forward Pixel Tracker	2,346	1,099	1,915	5,360	2,144	7,503	4,134	3,369
6	**Common Projects**	**22,238**	**0**	**0**	**22,238**	**0**	**22,238**	**19,055**	**3,183**
7	**Project Management**	**0**	**0**	**5,080**	**5,080**	**813**	**5,892**	**5,892**	**0**
7.1	Project Administration	0	0	2,651	2,651	424	3,076	3,076	0
7.2	Technical Coordination	0	0	2,428	2,428	389	2,817	2,817	0

US CMS NSF Cost Estimate

WBS Number	Description	US Mfg M&S (K$)	US Mfg Labor (K$)	US EDIA (K$)	US Base Cost (K$)	US Cont (K$)	Total US Cost (K$)	NSF Request (K$)
Total US CMS NSF Project Request								**20,032**
FY'96 R&D							100	100
US CMS Total NSF Estimated Cost		**13,134**	**1,528**	**1,368**	**16,030**	**3,902**	**19,932**	**19,932**
1	**Endcap Muon System**	**778**	**237**	**311**	**1,326**	**338**	**1,664**	**1,664**
1.1	**Muon Measurement System**	**778**	**237**	**311**	**1,326**	**338**	**1,664**	**1,664**
1.1.7	Alignment	778	237	311	1,326	338	1,664	1,664
1.1.7.1	System Development			200	200	44	244	244
1.1.7.2	Phi Global Linking	292	57	32	381	83	464	464
1.1.7.3	Local CSC Plane Alignment	486	180	79	745	211	956	956
2	**Hadron Calorimeter**	**4,404**	**907**	**140**	**5,451**	**1,635**	**7,086**	**7,086**
2.1	**Barrel Hadron Calorimeter (HB)**	**1,208**	**321**	**50**	**1,578**	**473**	**2,052**	**2,052**
2.1.1	Barrel	94	88	50	231	69	300	300
2.1.1.8	Prototypes	94	88	50	231	69	300	300
2.1.2	Barrel Late Shower Detector	1,115	233	0	1,347	404	1,751	1,751
2.1.2.3	Phototransducers	738	33	0	770	231	1,001	1,001
2.1.2.4	Electronics	377	200	0	577	173	750	750
2.2	**Endcap Hadron Calorimeter (HF)**	**3,196**	**587**	**90**	**3,873**	**1,162**	**5,035**	**5,035**
2.2.1	Endcap	2,304	356	90	2,750	825	3,575	3,575
2.2.1.2	Optical System	158	96	90	344	103	448	448
2.2.1.3	Phototransducers	1,608	60	0	1,667	500	2,168	2,168
2.2.1.4	Electronics	539	200	0	739	222	960	960
2.2.2	Endcap Late Shower Detector	892	231	0	1,122	337	1,459	1,459
2.2.2.3	Phototransducers	569	31	0	599	180	779	779
2.2.2.4	Electronics	323	200	0	523	157	680	680

US CMS NSF Cost Estimate

WBS Number	Description	US Mfg M&S (K$)	US Mfg Labor (K$)	US EDIA (K$)	US Base Cost (K$)	US Cont (K$)	Total US Cost (K$)	NSF Request (K$)
3	**Trigger/Data Acquisition**	**1,153**	**148**	**170**	**1,471**	**387**	**1,858**	**1,858**
3.3	**Luminosity Monitor**	**345**	**42**	**48**	**435**	**87**	**522**	**522**
3.3.1	Interaction Rate Monitor (2)	106	21	18	145	29	174	174
3.3.2	Beam Condition Monitor (6)	0	0	0	0	0	0	0
3.3.3	Roman Pot Detectors (6)	143	21	30	194	39	233	233
3.3.4	Power Supplies	42	0	0	42	8	50	50
3.3.5	Cables	35	0	0	35	7	42	42
3.3.6	Testing Facilities	19	0	0	19	4	23	23
3.4	**Data Acquisition System**	**808**	**106**	**122**	**1,036**	**300**	**1,336**	**1,336**
3.4.2	Readout Data Link (RDL)	313	32	122	467	135	602	602
3.4.2.1	Design and Document	20	0	48	68	20	88	88
3.4.2.2	Prototypes	28	0	37	65	19	84	84
3.4.2.3	Production	225	32	0	257	75	332	332
3.4.3.4	Installation and Test	40	0	37	77	22	99	99
3.4.3	Readout Crate Supervisor (RCS)	495	74	0	569	165	734	734
3.4.3.1	Design and Document	40	0	0	40	12	52	52
3.4.3.2	Prototypes	50	0	0	50	15	65	65
3.4.3.3	Production	405	74	0	479	139	618	618
3.4.3.4	Installation and Test	0	0	0	0	0	0	0

US CMS NSF Cost Estimate

WBS Number	Description	US Mfg M&S (K$)	US Mfg Labor (K$)	US EDIA (K$)	US Base Cost (K$)	US Cont (K$)	Total US Cost (K$)	NSF Request (K$)
4	**Electromagnetic Calorimeter**	**2,057**	**86**	**50**	**2,193**	**579**	**2,772**	**2,772**
4.1	**Barrel Photodetectors**	**2,057**	**86**	**50**	**2,193**	**579**	**2,772**	**2,772**
4.1.1	Characterization Test Stand	14	0	17	32	5	37	37
4.1.2	Prototypes	17	4	8	29	7	36	36
4.1.4	Procurement and Characterization	2,025	32	0	2,057	555	2,612	2,612
4.1.4.1	Prepare Specifications and Bid Package	0	3	0	3	0	4	4
4.1.4.2	Procure APD's	2,025	0	0	2,025	547	2,572	2,572
4.1.4.3	Characterization	0	15	0	15	4	19	19
4.1.4.4	Tracking	0	2	0	2	0	2	2
4.1.4.5	Final Inspection/Test	0	12	0	12	4	16	16
4.1.6	Project Coordination	0	50	25	75	12	87	87
5	**Tracking**	**1,559**	**150**	**697**	**2,406**	**963**	**3,369**	**3,369**
5.1	**Forward Pixel Tracker**	**1,559**	**150**	**697**	**2,406**	**963**	**3,369**	**3,369**
5.1.1	Detectors	991	0	206	1,197	479	1,676	1,676
5.1.1.1	Diode Arrays	991		206	1,197	479	1,676	1,676
5.1.2	FE Electronics	213	0	120	333	133	466	466
5.1.2.2	Data Collection Chip	213		120	333	133	466	466
5.1.3	Mechanical Support & Services	356	150	172	678	271	949	949
5.1.3.1	Kapton Interconnect	112	60	120	292	117	409	409
5.1.3.2	Fibers and Modulators	244	90	52	386	154	540	540
5.1.5	Calibration/Testing	0	0	198	198	79	278	278
5.1.5.2	Pixel Diode Array Chip Testing			124	124	50	174	174
5.1.5.3	Data Collection Chip Testing			74	74	30	104	104
6	**Common Projects**	**3,183**	**0**	**0**	**3,183**	**0**	**3,183**	**3,183**